FACTORS AFFECTING PREVALENCE AND DISTRIBUTION OF BITTER CRAB DISEASE IN NEWFOUNDLAND AND LABRADOR SNOW CRAB (Chionoecetes opilio): AN INVESTIGATION TOWARD FORMULATING FISHERY MANAGEMENT STRATEGIES

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Factors Affecting Prevalence and Distribution of Bitter Crab Disease in Newfoundland and Labrador Snow Crab (*Chionoecetes opilio)*: An Investigation Toward Formulating Fishery Management Strategies.

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Preface:

This report is submitted to partially satisfy the requirements for completion of the Master of Marine Studies in Fisheries Resource Management Programme at the Fisheries and Marine Institute of Memorial University of Newfoundland. As such, all statements and intellectual property contained herein are the responsibility of the author.

The report focuses on Bitter Crab Disease (BCD) in Newfoundland and Labrador snow crab (*Chionoecetes opilio*). Specifically, it investigates potential factors affecting prevalence and distribution of the disease toward formulating effective fisheries management strategies to deal with it. The report entails a review of snow crab biology, an overview of the Newfoundland and Labrador snow crab fishery, a literature review of BCD, and original research investigating prevalence and patterns of BCD in snow crab in coastal bays along the northeast coast of Newfoundland.

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1.0. Review of Systematics, Biology, Ecology, and Population Dynamics of Snow Crab

1.1. Taxonomy, Distribution, and Habitat:

The snow crab is a decapod crustacean. It is a brachyuran crab of the family Majidae, known as spider crabs. The species is circumpolar in northern latitudes, supporting commercial fisheries in the North Atlantic and Pacific Oceans (Dawe and Colbourne 2002). Snow crab in Newfoundland and Labrador are part of a larger stock complex spanning much of the northwest Atlantic, extending from the Gulf of Maine in the south to Labrador in the north, and encompassing the entire Gulf of St. Lawrence (Puebla et al. 2008). Snow crab can be captured across a wide range of depths (ie 20-1400m), from the tops of shallow banks to great depths along the edges of the continental shelf, with soft and muddy substrates preferred. Snow crab are most commonly found in waters <3°C (Tremblay 1997) and a thermal limit of 7°C appears to exist, above which the metabolic load is too great for normal respiratory function (Foyle et al. 1989, Tremblay 1997).

1.2 Molting, Mating, and Growth:

Molting, mating, and growth cycles of snow crab are highly complex and many aspects of them are poorly understood. There is regional variability in the timing of mating and molting and rates of growth. Furthermore, these life history characteristics are complicated by size, sex, and maturity stage.

The species is sexually dimorphic, with morphometrically mature males normally reaching larger sizes than mature females (Mullowney and Dawe 2009). In Newfoundland and Labrador, largest males can reach a maximum size of about 150 mm carapace width (CW), while largest females can achieve a size of about 95 mm CW (unpublished). Male and female snow crab develop differently. For males, immature, adolescent, and adult stages define the maturation cycle. Reproductive organs begin to function in the adolescent stage (Sainte-Marie et al. 2008), while a (final) terminal molt occurs when adulthood is achieved, during which time males develop enlarged claws (Conan and Comeau 1986). Growth occurs by molting. Immature (juvenile) crabs molt most frequently, at 8-10 month intervals (Sainte-Marie and Carrière 1995, Hébert et al. 2002), in contrast to adolescents (sexually mature but not adults) which molt on a near annual cycle each spring (Fonseca et al. 2008). However, in the adolescent stage,

crabs may skip a molt cycle (skip-molters) (Hébert et al. 2002) for which definitive reasons are unknown, but likely relate to temperature or host density. Size and age at terminal molt of males can be highly variable, ranging from about 40-150 mm CW (Sainte-Marie and Hazel 1992). Best estimates to reach commercial size (95 mm CW) are between 8-11 years (Hébert et al. 2002), and life expectancy after achieving terminal molt may be as long as 7-8 years (Fonseca et al. 2008).

For females, immature, pre-pubescent, pubescent, and mature stages define the maturation cycle (Sainte-Marie and Hazel 1992). Females become sexually mature upon their terminal molt, at which point a broadening of the abdomen occurs. Similar to males, size and age at terminal molt can be highly variable, ranging from about 30-95 mm CW (Alunno-Bruscia and Sainte-Marie 1998). Periodicity of molting is similar to that described for males, with molting frequency decreasing with increasing size and age.

Two types of mating occur at different times of the year. The first entails mating of recent terminally molted females, carrying their first clutch of eggs (primiparous); this mating occurs over-winter from January to March (Sainte-Marie and Hazel 1992). The second type of mating entails mating of females which have previously spawned (multiparous) and occurs in the spring (Taylor et al. 1984, Hooper 1986). In some instances, adolescent males may mate primiparous females (Watson 1970, Ennis et al. 1988, 1990), but mating of multiparous females is performed exclusively by adult males. This is due to selectivity of females in choosing mates and intense competition amongst males for access to females (Sainte-Marie et al. 2008). Females carry fertilized eggs for 1 to 2 years, with retention period normally being longer in cold regions, and extrusion occurring during February-April (Conan et al. 1989, Sainte-Marie 1993, Comeau et al. 1999), after which time mature females can re-mate or utilize stored sperm to fertilize future egg clutches (Conan and Comeau 1986). Larval hatching normally occurs in May-June, coincident with the phytoplankton bloom (Comeau et al. 1999) and settling of megalope occurs four to six months thereafter.

1.3 Migration:

Two types of migration occur; deepward ontogenetic migrations over the course of the crab's lifespan, and seasonal mating and molting migrations. Ontogenetic movements of male snow crab in NL can be inferred from distribution patterns observed in several studies, with largest crabs distributed at greater depths than smaller crabs throughout much of the year (Miller and O'keefe 1981, Taylor 1992, Dawe and

Colbourne 2002). This may be attributable to a shift in temperature preference from cold to warmer water as crab age and grow (Dionne et al. 2003). The scale of such movements can be quite variable, ranging from relatively short distances in coastal bays (Taylor 1992) to large distances in expansive offshore areas of the continental shelf, such as in the Eastern Bering Sea (McBride 1982, Ernst et al. 2005) and along the Eastern Scotian Shelf (Biron et al. 2008). Ontogenetic movements of females are extensive in the Bering Sea (Orensanz et al., 2004), but little is known of them in Atlantic Canada. Female movements in the Bering Sea may be driven by environmental factors. Accordingly, environmental conditions could cause movements of females to be more restricted in Atlantic Canada, as they appear to prefer to occupy areas of stable temperatures ranging from -1° to 1°C for much of their lives (Mallet et al. 1993, Comeau et al. 1999). This appears to be the case for females on the Grand Bank, which consistently occupy a depth range of 100-200 m, where cold water persists throughout the year (author, unpublished).

Spring movements of male and female crabs into shallow water for mating and molting were initially documented in Bonne Bay on Newfoundland's west coast (Taylor et al. 1984, Hooper 1986), and were subsequently described for snow crab populations throughout Atlantic Canada (Sainte-Marie et al. 1988, Brêthes and Coulombe 1989, Taylor 1990). Such movements appear to be most common in steep-sloped regions (ie bays and fjords). Peak sexuality occurs within 2-5.5 years following terminal molt (Fonseca et al. 2008). As not all crabs seasonally migrate, it may be that following peak sexuality seasonal migrations become less frequent or cease.

2.0. Overview of Snow Crab in Newfoundland and Labrador

2.1. History, Landings, and Value of the Fishery

The Newfoundland and Labrador snow crab fishery had a humble beginning, but has evolved to become the largest snow crab fishery in the world (Mullowney and Dawe 2009). Historically, crabs were taken as by-catch in gill-net fisheries directed at groundfish. A small-scale fishery targeting for snow crab began in Trinity Bay in 1967. The fishery remained confined to inshore bays of northeastern Newfoundland until the

mid 1980s before expansion began (Dawe et al. 2009a). Following the collapse of many groundfish stocks during the early 1990s, the fishery grew quickly with peak landings of 69,000 t in 1999 (Fig. 1). There were over 3500 licence/permit holders under enterprise allocation by 1999 (Dawe et al. 2009a), and that number has subsequently changed little.

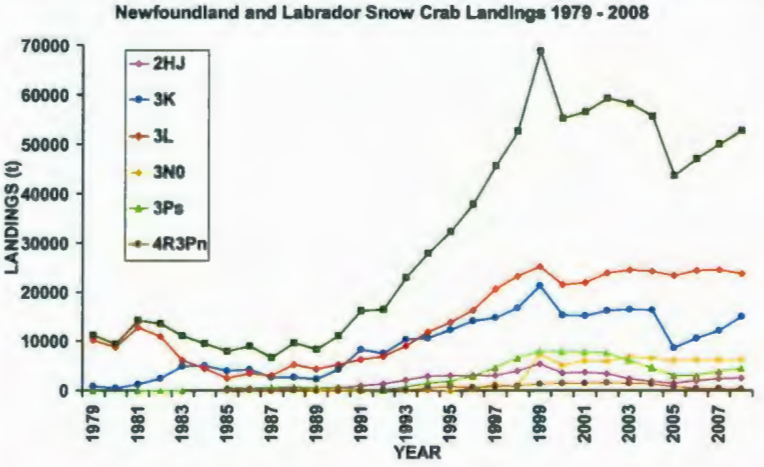

Figure 1. Newfoundland and Labrador snow crab landings. Source – DFO.

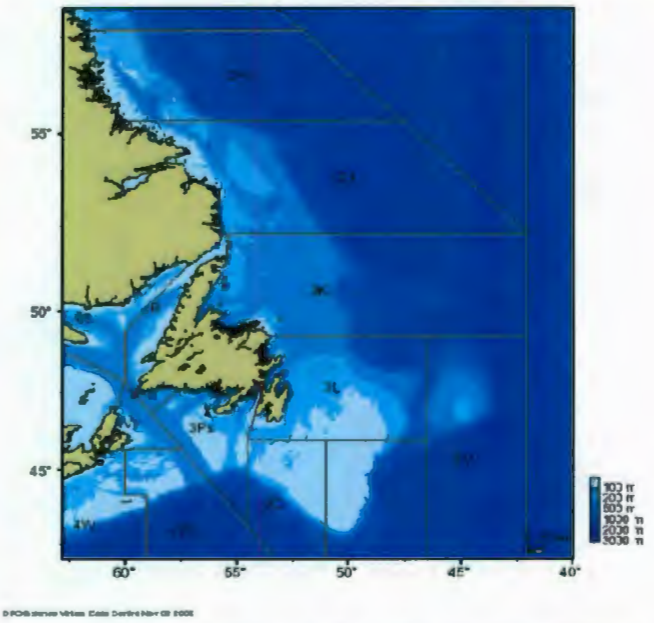

Figure 2. NAFO Divisions and bathymetrical features of the Newfoundland and Labrador continental shelf.

In the modern context, the snow crab fishery is the most important fishery in terms of social and economic values in NL, particularly in rural regions. Quota reductions have lowered the level of annual landings since 1999, but the fishery has remained large in scale, with landings exceeding 50,000 t in most years. In 2008, 52,775 t were landed from the Northwest Atlantic Fisheries Organization (NAFO) Divisions 2HJ3KLNOPns4R, spanning as far north as central Labrador and surrounding the entire Island of Newfoundland (Fig. 2). The landings have been valued at $150 - $200 million per year in recent years (DFO Statistics, unpublished).

2.2. *Management and Science of Snow Crab in Newfoundland and Labrador*

Management of snow crab in Newfoundland and Labrador is not conducted at the stock level, but at smaller scale units known as Crab Management Areas (CMAs) (Fig. 3). As the stock of snow crab in the Northwest Atlantic extends across several international and regional boundaries, and the mobility of crabs is such that individuals occupy only a small fraction of the range throughout their lives, management at the stock level is deemed inappropriate. Annual quotas, referred to as Total Allowable Catches (TACs), are partitioned among individual quota (IQ) holders in nearly fifty CMAs with the aim of achieving a broad spatial distribution of effort (Mullowney and Dawe. 2009). Several fleet sectors exist in the fishery, with larger vessels generally exploiting offshore CMAs and smaller vessels exploiting near-shore CMAs. Fleet sectors include the Communal Fleet, primarily comprised of Aboriginal fishers in northern regions, the Full-time Fleet, generally represented by large vessels (ie 45-65 ft.) operating offshore, the Large Supplementary Fleet, consisting mainly of large vessels (ie 45-65 ft.) operating offshore, the Small Supplementary Fleet, represented predominately by small (ie 35-45 ft.) vessels operating offshore, and the Inshore Fleet, consisting of <35 ft. vessels fishing in near-shore regions and bays. The term 'supplemental' in fleet designations signifies licenses granted during the decline and eventual collapse of groundfish stocks in the early 1990s.

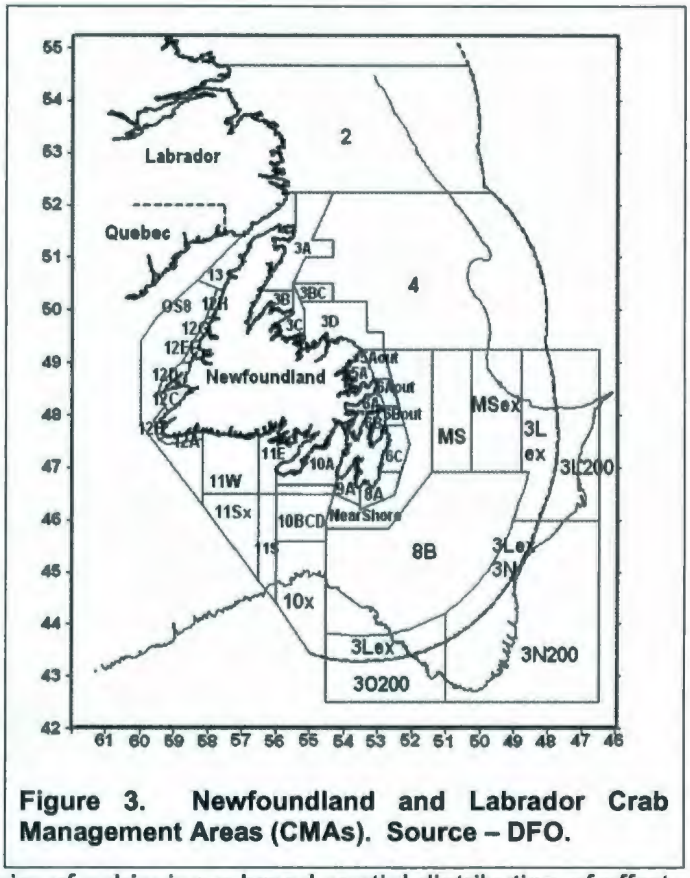

Figure 3. Newfoundland and Labrador Crab Management Areas (CMAs). Source – DFO.

Management controls are stringent in this fishery. The fishery is prosecuted by deploying and retrieving long-lines of baited pots, known as 'fleets' (Dawe et al. 2009b).

The pots most commonly used are Japanese-style conical traps, spanning 50" across the bottom (Fig. 4). Management regulations limit the mesh size of pots to a minimum of 135 mm to allow escapement of females and small males. Regulations further limit the retention of crabs to males of =95 mm carapace width (CW). These regulations help maintain the reproductive potential of the stock by ensuring that females and a portion of adult males in the population remain unexploited. Other management controls include pot limits, trip (landings) limits, seasonal restrictions, and fishery closures during periods of high occurrence of soft-shelled crab catches. Until recently, most fishing occurred in the summer, with lesser amounts of effort in the fall. However recent management regulations have shifted such that most fishing is conducted during spring (Dawe et al. 2009b). This shift in seasonality of the fishery is intended to reduce catches of soft-shelled crab and minimize associated capture mortality (Mullowney and Dawe, 2009). Other regulations include mandatory completion and submission of fishing logbooks, at-sea observer coverage on 10% of commercial trips, a requirement of offshore vessels to have an operable vessel monitoring system (VMS) device, and all offloads to be monitored at dockside.

Figure 4. Typical gear used in NL snow crab fishery. Source – Codend.ca

Scientific assessments of resource status are conducted annually. As the CMAs used to manage the fishery have no biological relevance, assessments are conducted at the larger-scale NAFO Division level, with inshore and offshore regions considered separately, to partially conform with management areas while accommodating different types and amounts of available information (Dawe et al. 2009b). These assessments incorporate data from trap and trawl surveys, commercial logbooks, at-sea observer sampling/monitoring, VMS, and dockside monitored landings to assess trends in biomass, recruitment, production, and mortality (Dawe et al. 2009b).

3.0. Bitter Crab Disease (BCD)

3.1. What is BCD, and what are its effects?

Figure 5. Ventral view of snow crab infected with BCD (left) versus uninfected (right). Source – Dave Taylor, DFO.

BCD is caused by a parasitic dinoflagellate of the genus *Hematodinium*. *Hematodinium spp.* infect many species of decapods, proliferating in crustacean hemolymph (the circulatory fluid of invertebrates, ie blood). In snow crabs, *Hematodinium* infection by these parasites results in a condition commonly referred to as Bitter Crab Disease (BCD). The parasite indirectly removes hemocytes and osmotically consumes hemolymph respiratory proteins, creating an increased metabolic load on infected hosts. This usually results in host death due to organ and/or respiratory dysfunction (Meyers et al. 1987, Love et al. 1993), as the need for oxygen increases while the oxygen carrying capacity of the hemolymph decreases (Stentiford and Shields 2005). Hemocytes are important in wound repair, clotting, phagocytosis, nodulation, and encapsulation of foreign material. A reduction in hemocyte levels leads to an inability of the hemolymph to clot (Sheppard et al. 2003), and may render crabs vulnerable to co-infection by additional parasites and pathogens (Meyers et al. 1987, Shields et al. 2003, Walker et al. 2009). The parasite infiltrates the connective tissues of all host organs, resulting in degredation of lost tissues (Sheppard et al. 2003, Stentiford and Shields 2005). In chronically infected cases, the ventral side of the limbs becomes an uncharacteristic opaque, bright white colour (Fig. 5). The degradation in quality of the meat is likely attributable to an alteration in carbohydrate supply to active muscles (Stentiford et al. 2000b). The discolouration of the shell likely reflects glycogen depletion and/or an alteration in synthesis and release of pigment dispersing and concentrating hormones (Stentiford and Shields 2005).

BCD is an economically and biologically significant factor in crustacean host populations, and consequently in crustacean fisheries. Mortality from BCD threatens future recruitment and the viability of infected host populations (Meyers et al. 1990), and is capable of decimating natural crab populations (Meyers et al. 1987).

Behavioural changes in the host can include anorexia and lethargy (Meyers et al. 1987), or a requirement to spend increased amounts of time foraging to satisfy the increased metabolic demand, rendering infected hosts more susceptible to predation (Stentiford et al. 2001b).

Globally, the range of distribution of infection by *Hematodinium spp.* has increased in recent years, as has the number of infected host populations (Morado et al., 2010). BCD was first discovered in NL snow crab in Bonavista Bay in 1990 (Taylor and Khan 1995). It exhibits a negative biological impact on the snow crab resource because it is 100% fatal to its host (Dawe 2002). Furthermore, there is potential for negative economic impacts as infected crabs are rendered unmarketable due to the chalky texture and bitter flavour of the meat and 'cooked' appearance of the shell (Meyers et al. 1987, Taylor and Khan 1995, Chualain et al. 2009).

3.2. Management strategies for BCD in Newfoundland & Labrador Snow Crab

At present, no formal regulations exist to deal with BCD, although fishery managers urge fishermen to keep, isolate, and return infected crabs to shore for disposal at landfill locations. In exchange, the weight of infected crabs returned to shore is not deducted from quotas (personal communication, Tony Blanchard, DFO).

As part of the annual resource assessments on mortality, trends in prevalence of BCD are examined. However, because there are high levels of uncertainty regarding true prevalence of BCD in the snow crab population, and a multitude of unknown factors controlling for its distribution, scientific consensus on the impacts of the disease is difficult to achieve. Consequently, little advice is available to fishery managers on how to incorporate this mortality factor into the management regime, and little regard is given to it in year-to-year management of the fishery (personal communication, Tony Blanchard, DFO). Increased knowledge of BCD related mortality may allow managers to more effectively plan harvest levels and strategies.

3.3. What do we know about BCD in NL snow crab?

Very little is known with certainty about processes affecting BCD transmission, prevalence, and distribution in NL snow crab. BCD prevalence is variable by location and year in NL snow crab (Dawe 2002, Pestal et al. 2003, Shields et al. 2005, 2007, Wheeler et al. 2007). Globally, this appears to be a general characteristic in nearly all cases where *Hematodinium* affects crustacean populations (Stentiford and Shields,

2005). BCD is most common in new-shelled or recently molted snow crab in NL (Dawe 2002, Pestal et al. 2003, Shields et al. 2005, 2007, Wheeler et al. 2007). Again, this is consistent with most studies on *Hematodinium* world-wide (Stentiford and Shields 2005). There is consensus on the seasonality of infection intensity in NL snow crab, with the disease most readily apparent in the fall (Dawe 2002, Pestal et al. 2003, Shields et al. 2005, 2007, Wheeler et al. 2007). Seasonality of infection intensity is a common trait of parasitism by *Hematodinium* in most crustacean populations, but differs by host species and region (Stentiford and Shields 2005). Finally, it is known that macroscopic observations, upon which most estimates of BCD in NL snow crab are based, underestimate true prevalence as only terminal infections are readily detectable by visual examination (Dawe 2002, Pestal et al. 2003).

3.4. What do we need to learn about BCD in NL snow crab?

Overall, there is no definitive understanding of how transmission occurs, true prevalence levels in the population, and little understanding of distribution patterns. At the most basic level, there is uncertainty regarding the medium in which parasitic transmission occurs. The most common perspective is that infective stages are located in the water (Eaton et al., 1990, Frisher et al., 2006, Stentiford and Shields, 2005). Eaton et al. (1990) found that the period of sporoulation in the parasite life cycle (Fig. 6) overlapped with that of molting for Tanner crabs in Alaska, and speculated transmission of the infective stage occurred at that time. Similarly, Stentiford and Shields (2005) surmised that released parasites formed cryptic blooms in the water column that put crustacean hosts at risk of contracting the disease. To investigate the matter, Frischer et al. (2006) suspended uninfected blue crabs (*Callinectes sapidus*) in cages, with some becoming infected after just one day exposure to water containing *Hematodinium* dinospores. Shields et al. (2005, 2007) extended the realm of possibilities for the medium of transmission, suggesting that substrate also played a role

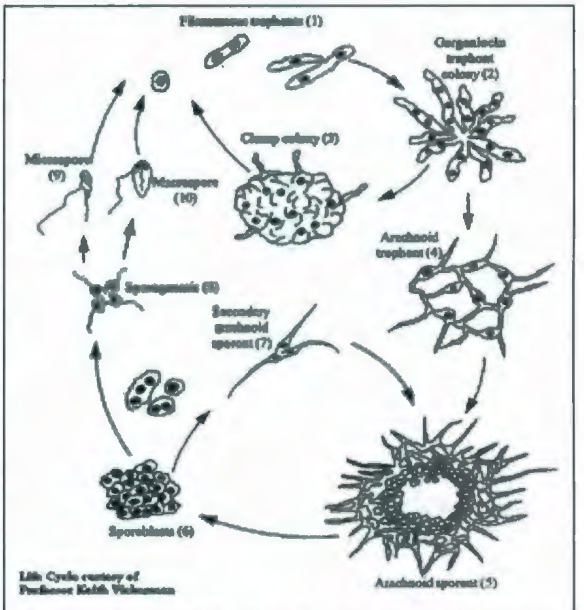

Figure 6. Life Cycle of *Hematodinium* parasites. Source – University of Glasgow.

in parasitic transmission for snow crab in Conception Bay, NL. They showed a statistical association between BCD prevalence and sand/muddy substrate. However, there may have been strong bias in this finding, as the surveys targeted almost exclusively sand/muddy substrates.

Modes of transmission are uncertain, but studies on NL snow crab generally agree that transmission of the disease is associated with molting. This is supported by the observation that most infections occur in new-shelled animals (Dawe 2002, Pestal et al. 2003, Shields et al. 2005, 2007, Wheeler et al. 2007). However, transmission could also occur by physical contact (Stentiford and Shields 2005), filter feeding (Stentiford et al. 2001a), or cannibalism (Meyers et al. 1990, Stentiford et al. 2000a, Walker et al. 2009). In fact, in a recent study by Walker et al. (2009) on blue cabs on the east coast of the United States, whereby non-infected hosts were fed infected tissues, showed 73 % of experimental hosts contracted *Hematodinium* infections within two days of ingesting infected material.

The list of variables to be considered with respect to uncertainties associated with true prevalence levels and distribution patterns of BCD in NL snow crab is extensive. The forthcoming sections examine problems and knowledge gaps associated with specific factors that can bias interpretation of data and information.

3.4.1. Macroscopic vs. microscopic observations:

Visual examination underestimates true prevalence levels of BCD as latent and early-stage infections are not easily detected (Stentiford et al. 2001a, Dawe 2002, Pestal et al. 2003, Stentiford and Shields, 2005, Chualain et al. 2009). Pestal et al. (2003) compared macroscopic and microscopic (bloodsmear) observations from Conception Bay snow crab, finding only 53 % of infected crabs were detected by eye. This underestimation closely agrees with Stentiford et al. (2001a), who estimated about 50 % of infected cases in Norway Lobsters (*Nephrops norvegicus*) were missed by visual classification. Clearly, true prevalence levels are greatly underestimated by visual examination. An on-going study encompassing trap and trawl based samples from inshore and offshore areas of NL being examined with advanced diagnostic polymerase chain reaction (PCR) methods will reveal more on this issue, and should allow for better estimates of true prevalence levels.

3.4.2. Capture method - traps vs. trawls:

Most researchers, both in NL and globally, have concluded that trawls serve as a superior gear to traps for interpreting true prevalence levels and distribution patterns of *Hematodinium* in diseased populations. The basic logic is that trawls capture a more representative sample of the population, as traps tend to select for larger-sized animals (Wilhelm and Mialhe 1996, Dawe 2002, Pestal et al. 2003, Stentiford and Shields 2005, Shields et al. 2005, 2007). Taylor and Khan (1995) also speculated that trawls are superior because infected crabs may be too weak to enter baited traps, thus traps would underestimate true prevalence. However, Stentiford et al. (2001a) suggested the exact opposite effect in Norway lobsters, speculating that increased nutritional demands, and hence increased catchability of infected lobsters, led to an overestimation of true prevalence levels.

In NL, there are inconsistencies in the literature to consider before concluding trawl-based data are superior to traps for interpreting BCD prevalence levels in snow crab. Offshore prevalence, as measured from multi-species trawl surveys, consistently indicate lower levels of BCD than inshore trap surveys (Dawe et al., 2009b). It may be reality that levels of BCD in the offshore are simply lower than inshore regions, as suggested by Shields et al. (2005, 2007), however it has been shown that the gear used in the offshore survey is inefficient at capturing all sizes of crabs, and that the inefficiency increases as size decreases (Dawe et al. 2010a). Sampling bias from the gear may lead to inaccuracies in interpreting true prevalence levels in the offshore (Dawe 2002). Similarly, sampling bias from traps may lead to bias in interpreting prevalence in the inshore, as traps do not capture smallest crabs. Shields et al. (2005, 2007) recommended trawls as a better method of measuring BCD in snow crab in NL based on comparative trap-trawl sampling in Conception and Bonavista Bays. However, an objective examination of the data presented in those studies reveals trapped females were omitted from analysis in 2005, while in 2007 there was only a slight difference in prevalence levels across the two gear types in males, and a higher percentage of BCD infection in traps than in trawls for females. Similarly, Dawe et al. (2009b) showed that prevalence has been consistently higher in trapped than trawled samples for all males >40 mm CW from Conception Bay since 1998.

Presently, there is conflicting and incomplete information on the effectiveness of these two gear types for measuring BCD in NL snow crab that renders it impossible to ascertain true prevalence levels in the population. The best approach is to critically

consider the gear-specific sampling bias when interpreting trends in BCD. PCR detection methods may eliminate this bias, as it may only be applicable to visually detectable or terminal cases.

3.4.3. Circulation and Bathymetry:

Circulation and bathymetry features may influence distribution and prevalence of BCD in crustacean hosts. The general assertion is that higher prevalence may occur in confined embayments with little flushing by tides and currents (Meyers et al. 1987, 1990, Eaton et al. 1990, Field et al. 1998, Messick and Shields 2000, Stentiford and Shields 2005). The circulation and bathymertrical features of the Newfoundland and Labrador shelf are very dynamic (Fig. 7). A strong, southerly flowing (cold) oceanographic current known as the Labrador Current affects the region. The weaker inshore branch flows over the top of the continental shelf and into an extensive series of isolated bays along the northeast coast of Newfoundland. The stronger offshore branch flows along the slope edge, generally remaining to the east of large, shallow banks that constitute much of the underwater physical terrain. As such, circulation and bathymetric features would infer that BCD prevalence should be higher in inshore regions because retention time of water would be greater, as suggested by Shields et al. (2005, 2007). Furthermore, current research focusing on the offshore indicates prevalence levels are lowest in regions that are influenced by the strongest flowing components of the Labrador Current, such as along the slope edges (Dawe et al., 2010b). To date, most information suggests that areas having a higher likelihood of water containment or recirculation may exhibit higher levels of BCD. This phenomenon may reflect common advection patterns between settling stages in the host's life cycle and waterborne phases of the parasite's life cycle (Dawe et al. 2010b). At present

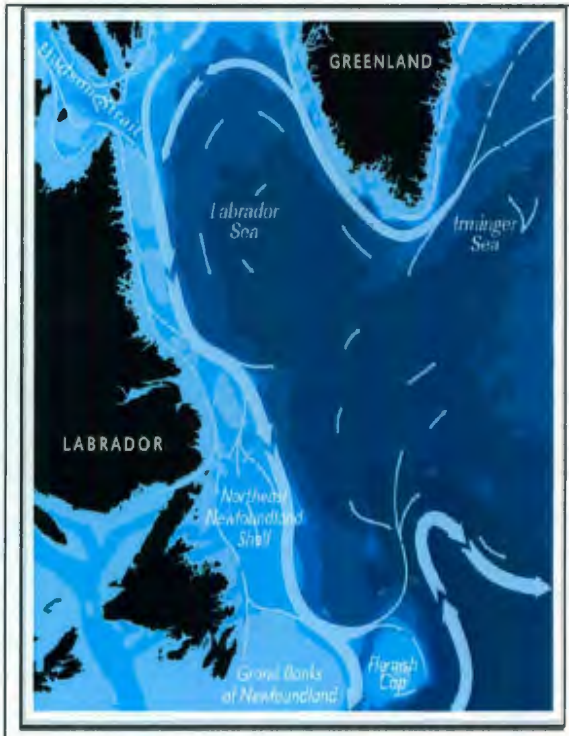

Figure 7. Model of current patterns in the Northwest Atlantic. Source – DFO.

however, the association between oceanographic properties and BCD prevalence and distribution is strictly qualitative, with no quantitative link.

3.4.4. Temperature:

There is no consistent information on the influences of temperature on BCD prevalence and distribution, as the literature is highly varied on the issue. The effects of temperature may differ across species and region (Stentiford and Shields 2005).

In blue crab in the northeastern U.S.A., prevalence and intensity of infection is lowest at low temperatures and highest at intermediate to high temperatures during summer (Messick 1994, Messick et al. 1999, Shields and Squyars 2000). Increasing temperatures appear to cause latent infections to become patent. This implies a seasonality effect in the parasite's life cycle, as it can infect a host at low temperatures, but not actively proliferate until temperature increases. Parasitic cells can exhibit logarithmic growth within hemolymph (Stentiford and Shields, 2005), thus it may be that as temperature increases so does the rate of replication of infected cells. Messick et al. (1999) found that in blue crabs, *Hematodinium* did not proliferate below 9°C and speculated that areas where there is no seasonality of *Hematodimium* infection intensity, such as Australia, may be characterized by consistent high water temperatures. It is noteworthy that bottom temperatures along the Newfoundland-Labrador shelf very rarely (if ever) reach 9°C. Therefore, it is questionable whether the same species of *Hematodinium* infects NL snow crab, or if the parasite infecting snow crab develops and/or operates in the same fashion as it does in blue crab.

Chualain et al. (2009) found that highest infection intensities in the Irish brown crab corresponded with moderate and decreasing water temperatures in fall. They concluded that although there was no seasonality in prevalence of the disease, there was seasonality in infection intensity. The study showed that peak temperature occurred four months before peak intensity. In contrast to the pattern described for blue crab, the authors speculated that cooling in the fall initiated division of the parasitic cells and proliferation of the disease.

In the snow crab, there is a distinct seasonality to intensity of BCD infection, with chronic cases most readily detectable in the fall and rarely observed during spring (Dawe 2002, Pestal et al. 2003, Shields et al. 2005, 2007, Wheeler et al. 2007). Bottom temperatures along the Newfoundland-Labrador shelf are normally warmer in fall than in spring (Colbourne et al. 2009). Therefore, the pattern suggests that infection intensity

could be positively related to temperature. This idea was advanced by Shields et al. (2007) who described temperature-induced mass molts of large adolescent male snow crab in Conception Bay in 2003-2005 that resulted in an epizootic outbreak of BCD. They suggested future climate warming would enhance transmission of the parasite and dispersion of the disease. However, this line of reasoning is inconsistent with an earlier paper on BCD in snow crab in Conception Bay, where they noted the parasite thrived at low temperatures (Shields et al. 2005). Furthermore, since 2007, water temperatures along the Newfoundland-Labrador shelf have remained above normal (Colbourne et al. 2009), while prevalence levels of BCD have declined both in the offshore as well as in Conception Bay (Dawe et al., 2009b). The temperature-induced mass molt theory is also questionable in that the molting phenomenon was apparently limited to a select size group of males, and females did not exhibit increased molting activity during those years (Shields et al. 2007).

The case for a temperature-BCD relationship in NL snow crab is weak, and highly speculative. The issue requires further research to formulate a definitive cause and effect relationship.

3.4.5. Salinity:

There is little information available on the effects or relationships of salinity with BCD infection in NL snow crab. However, in investigating potential reasons for the lack of BCD in snow crab from the Gulf of St. Lawrence, it has been suggested a potential salinity buffer exists, at 32 ppt, below which BCD infection is uncommon in snow crab (author, unpublished). Dawe et al. (2010b) show a similar phenomenon for offshore populations of snow crab along the NL shelf, with little BCD encountered in salinities below 33 ppt.

An association has been made between BCD and salinity in blue crab, whereby infection rarely occurs below 11 ppt, and intensity of infection increases as salinity increases (Messick et al. 1999). Frischer et al. (2006) speculated the dinospore stages of the parasite are susceptible to changes in salinity and do not tolerate low levels. This is consistent with Messick and Shields (2000) who noted patterns of BCD distribution in blue crab reflected patterns of salinity throughout the habitat range. Again, similar to temperature, it is worth noting the large difference in tolerance levels of salinity between snow crab (32-33 ppt) and blue crab (11 ppt), which may infer a different species of parasite at work.

In a study of BCD in the Irish brown crab, Briggs and McAliskey (2002) showed a positive correlation of BCD prevalence with salinity. However, salinity levels remained between 34-35 ppt, thus it could be argued the range of salinity was inadequate to make such a comparison. Moreover, Stentiford and Shields (2005) noted that most infections of *Hematodinium* have been reported in stenohaline species that experience only minor variations in ambient salinity, such as the Irish brown crab example. In NL, regional and depth related differences occur in the salinity profile as well as in BCD levels for snow crab along the continental shelf, thus this may be a good study area to examine such a hypothesis.

3.4.6. Distribution and Migration:

Patterns of BCD prevalence in NL snow crab populations are variable by time and space (Dawe 2002, Pestal et al. 2003, Shields et al. 2005, 2007, Wheeler et al. 2007). Thus, spatial-temporal shifts in distribution of the host may influence proliferation of the disease. Chualain et al. (2009) suggested that migrations in the Irish brown crab likely influenced their vulnerability to infection by *Hematodinium*.

The migratory movements of snow crab were detailed in Section 1.3 of this report. Generally, seasonal migrations result in some mating crabs being distributed shallower in spring than in fall, and ontogenetic migrations lead to a tendency for males to be segregated by size and depth, with large crabs found deeper than small crabs (Dawe and Colbourne 2002). Meyers et al. (1987) found no difference in BCD prevalence across depths in the closely related Alaska Tanner crab, and globally, research results showing direct associations between BCD prevalence and depth have been limited. However, uniquely, a direct relationship between prevalence and depth was detailed for snow crab in Conception Bay. Shields et al. (2005, 2007) showed that prevalence was highest at greatest depths and concluded that prevalence increased with depth. However, it can be argued that these studies failed to adequately sample depths <200 m, and did not fully consider the movement of crabs. Together, these two points highlight major concerns. The surveys focused primarily upon deep regions (ie. >200 m), and were exclusive to the fall of the year, thus they were not representative of the entire spatial-temporal distribution of crabs. The findings of Shields et al. (2005, 2007) do not reflect trends that occur across the more broad-scale distribution of snow crab in NL. Dawe (2002) showed BCD was encountered across much of the expansive continental shelf, encompassing a wide range of depths. In fact, in most years BCD was

commonplace atop the Funk Island Bank in Div. 3K, and in 1999, BCD was especially prominent atop of the Hamilton Bank in Div. 2J. These areas are shallow in relation to the majority of the snow crab habitat surrounding NL. The cause and effect relationship between depth and BCD prevalence suggested for Conception Bay is likely biased by sampling methods, thus the conclusion that BCD is most prominent at deep depths is not warranted.

Susceptibility to BCD infection by depth and/or migration could easily be confounded by several other variables including population structure, temperature, salinity, substrate, sampling (gear) efficiency, and predator abundance. Moreover, interpreting depth-specific differences in BCD prevalence may be very difficult, as various inter-connected abiotic and biotic factors need to be understood. For example, in snow crab, high prevalence in shallow regions could reflect high abundance of juvenile crab. In such a scenario, it may be incorrect to directly relate BCD prevalence to depth, as size could be the determinate factor. The complexities and difficulties of associating BCD prevalence with depth and/or migration may be the reason most researchers have been unable to make a formal connection.

3.4.7. Host Population Structure - Sex, Size, Host Density:

Population structure differences across sites and years can affect prevalence levels of BCD (Stentiford et al. 2001a, Pestal et al., 2003, Stentiford and Shields, 2005). Juveniles may be more susceptible to *Hematodinium* infection because of high population densities that predispose them to the parasite, or mature crabs may appear less susceptible due to their removal by the fishery or premature removal by infection (Messick and Shields, 2000). It is known that recently molted (new-shelled) crabs are more susceptible to BCD, however other factors such as sex, size, and host density could also be contributing factors.

Sex: The effect of sex on BCD prevalence appears to be species-specific. There is no difference in BCD prevalence by sex in the Alaska Tanner crab, (Meyers et al. 1987, 1990), the blue crab (Messick 1994, Messick et al. 1999, Messick and Shields 2000), or the velvet crab in France (Wilhelme and Mialhe 1996). However, in the Norway lobster (Stentiford et al. 2001a, Briggs and McAliskey, 2002) and NL snow crab (Dawe 2002, Pestal et al. 2003, Shields et al. 2007) prevalence appears to be higher in females. It is unknown to what extent these species-specific differences could be confounded by different fishing strategies or exploitation rates. For example, sex-

specific percentages could be skewed in male-only fisheries, or sex-specific differences in BCD prevalence could be attributable to size differences across sexes, such as is in sexually dimorphic species like the snow crab.

Size: In most species, *Hematodinium* infections show distinct patterns with size of the host (Stentiford and Shields, 2005). Generally, prevalence tends to be highest in small animals (Messick, 1994, Messick and Shields, 2000, Stentiford et al. 2001a, Briggs and McAliskey 2002, Chualain et al. 2009). In NL snow crab, a size versus prevalence relationship is uncertain because studies have yielded results inconsistent with the pattern of highest prevalence in smallest animals. Dawe (2002) found prevalence was highest in intermediate-sized (41-59mm CW) males, while Shields et al. (2007) found prevalence was highest in large adolescent males, which they attributed to temperature-induced mass molting events in large adolescents. In the case of Dawe (2002), it may be that macroscopic observations on smallest animals were unreliable, while in the case of Shields et al. (2007), it may be that changes in demographics of the population structure accounted for size differences of infected hosts, rather than an environmental shift exerting unique effects upon a specific portion of the population. During 1999-2000, there were very few large-sized (ie. =65mm CW) adolescent males in the Conception Bay snow crab population, whereas during 2003-2005 a high proportion of crabs of this size were adolescent (Dawe et al. 2009b). The apparent mass molt likely simply reflected a recruitment pulse progressing through to larger sizes, evident by a distinct modal progression in size frequencies examined in resource assessments (Dawe et al. 2009ab).

Host Density: Spatial and temporal changes in BCD prevalence may be related to changes in host density (Dawe 2002, Sheppard et al. 2003). This effect may be evident in changes in the density of the population as a whole, or it could be restricted to changes in density within sub-components of the population. As parasite transmission is associated with molting, changes in the abundance or proportion of the population that are recently molted may best reflect trends in BCD prevalence. In the case of snow crab, this would be manifested in juvenile and adolescent crabs, which, excepting skip-molters, are classified as recently molted animals (within the past year). Although no quantitative link of host density versus BCD prevalence in snow crab has yet been made, it is an area of research that merits further consideration, as one may be able to predict future BCD-induced downturns in the fishery by tracking disease prevalence in sub-components of the population rather than in the population as a whole.

4.0 Original Research – Factors Affecting Prevalence of BCD

4.1. Context

There has been a reduction in abundance of smallest (ie =40 mm CW) crabs in the fall trawl survey since 2003, as reflected by the abundance of small males (Fig. 8). This implies reduced abundance of commercial-sized crabs that will be available to the fishery in future years. Specific reasons for this reduction are unknown, but could include a number of factors such as a warming oceanic regime, an increase in the abundance of predatory groundfish, or other sources of mortality such as the presence of BCD in the population.

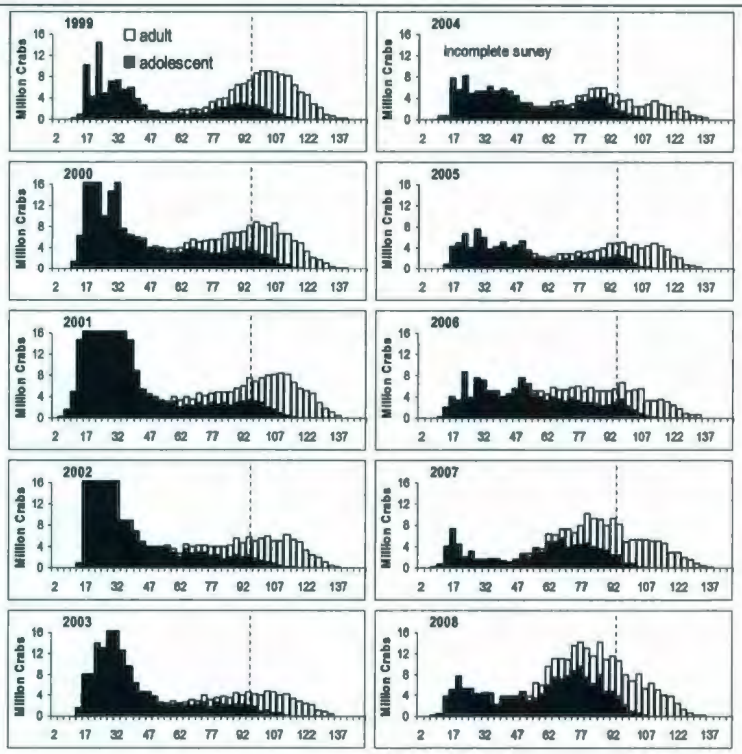

Figure 8. Size frequency distribution of abundance of male snow crab in NAFO Div. 2J3KLNO from fall multi-species trawl surveys (offshore). Source – DFO.

Each year trends in BCD prevalence are examined as part of the NL snow crab resource assessment. Although BCD constitutes a source of mortality, little is known about what factors influence trends, or how annual changes in prevalence will influence future population dynamics. The forthcoming analyses examine several factors which may influence prevalence levels of BCD in Newfoundland and Labrador snow crab, and gain a clearer understanding of potential impacts on the population for developing management strategies to effectively deal with them.

4.2. The Survey

The data used in this analysis come from an annual snow crab survey that occurs in White Bay and Notre Dame Bay along the northeast coast of Newfoundland (Fig. 9). The survey is a good choice for examination of trends in BCD for several reasons. Firstly, the survey is conducted in the fall (Sept.), coincident with apparent peak infection intensity of BCD, thus it maximizes the probability of visually detecting infections. Secondly, there is strong internal consistency in the data as there has been little change in personnel throughout the years, minimizing subjective bias. Finally, the survey targets a range of depths from 200-500 m (Fig. 9) within two independent bays, each with a different bathymetric make-up. White Bay is a deep fjord-type environment, protected at the mouth by a shallow sill and is deepest inland, whereas Notre Dame Bay is more of an open ocean-type environment that generally gets deeper with distance from shore (Fig. 9). No survey was conducted in 2001, and catch rates were low across all strata in 2004 which may indicate a catchability effect in that year (Dawe et al. 2009a).

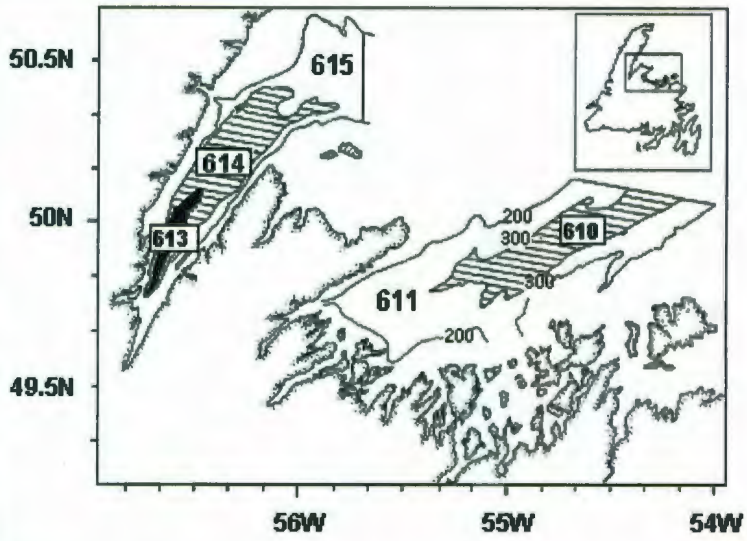

Figure 9. Map of survey strata in White Bay and Notre Dame Bay. Source – DFO.

Fig. 10. Canadian Coast Guard Vessel *Shamook*. Source – DFO.

The Canadian Coast Guard vessel *Shamook* (Fig. 10) served as the surface platform for all surveys since 1994. Survey sets consist of long-lines (fleets) of baited

traps (squid/mackerel) deployed for standardized soak times of 24-48 hours. The survey targets eight randomly assigned stations within each of five pre-defined depth strata (Fig. 9) each year. Each fleet of gear consists of six traps, with sampling conducted from two large-meshed (commercial, 135mm) and two small-meshed (27mm) traps. Small-mesh traps alternate with large-mesh traps within the configuration of those sampled from each fleet (ie. does not include two large-meshed end traps). Male crab are counted and sampled for size (CW), shell condition, claw height (mm), and presence or absence of BCD as per Dawe et al. (2009b). Capture of females is less common so the study was limited to males. Shell condition is classified as soft, new hard, intermediate, and old hard, which approximates time elapsed since molting. "Maturity" status is determined by applying claw heights to a regression equation segregating two clouds of data representing adult versus adolescent crabs as per Dawe et al. (2009b).

4.3. Sampling Bias

The traps used in the survey create bias in the data in that they select for large-sized crabs. This bias is clearly lesser in small-meshed traps (27mm), which retain a greater number of crabs between 35-86 mm CW (Fig. 11), and are therefore more representative of the population as a whole. As BCD is normally most prominent in small crabs, poorly captured by large-mesh traps, this study limits the analysis to data from small-meshed traps. It is recognized some sampling bias remains however, as smallest sizes of crabs are still poorly sampled and crabs < 32 mm CW are non-existent in the samples.

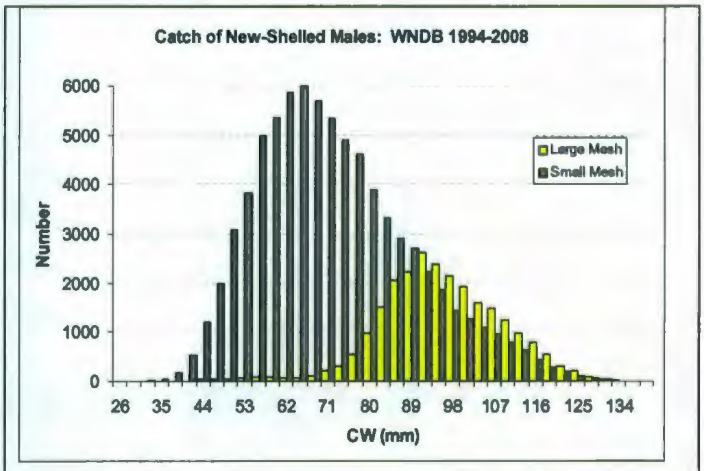

Fig. 11. Sample sizes and distribution of new-shelled males, by 3mm carapace width groupings, for small and large-meshed traps.

4.4. Overall Prevalence

There has been spatial-temporal variability in prevalence of BCD across the two bays, with peaks in Notre Dame Bay preceding peaks in White Bay by 1-2 years. Overall, prevalence has been greatest in new-shelled crabs (Fig. 12), consistent with the literature on *Hematodinium* outbreaks throughout the world. For this reason, further

analyses focus exclusively upon new-shelled animals. Two pulses of infection have occurred. In the original 1995-2000 period, prevalence peaked in Notre Dame Bay in 1996, with 17% of new-shelled crabs infected. Prevalence then peaked two years later in White Bay, with 13% of new-shelled crabs infected. In the second outbreak of 2003-2008, prevalence peaked in Notre Dame Bay in 2004 with 20% of new-shelled crabs infected, which was followed a year later by a peak of 18% in new-shelled crabs in White Bay.

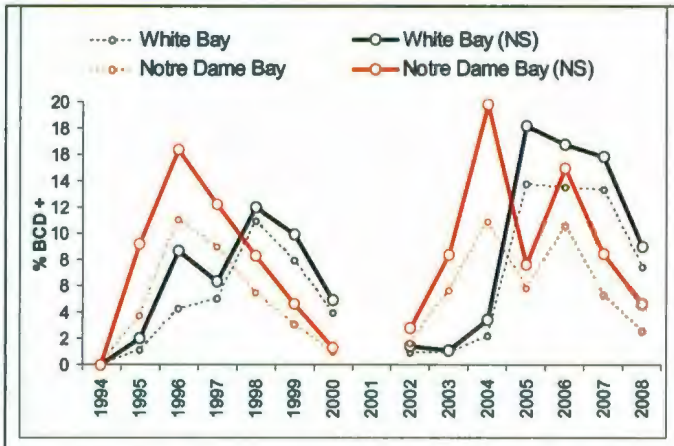

Fig. 12. Trends in prevalence of BCD by bay. New-shelled (NS) males versus all males.

4.5. Maturity (Adolescents versus Adults)

In both bays, prevalence has been greater in adolescent than adult crabs (Fig. 13). For this reason, further (non-host density related) analyses focus exclusively on adolescents. In White Bay, peaks of infection occurred in new-shelled adolescents in 1996, 1998, and 2005. In Notre Dame Bay, prevalence remained stable, at 16-17% in new-shelled adolescents (from 1995-1998) during the initial outbreak, while two defined peaks (in 2004 and 2006) occurred during the second outbreak. It is unknown whether sharp decreases in prevalence, such as occurred in White Bay in 1997 and in Notre Dame Bay in 2005, represent real phenomena or if a bias of some fashion exists in the data in those years.

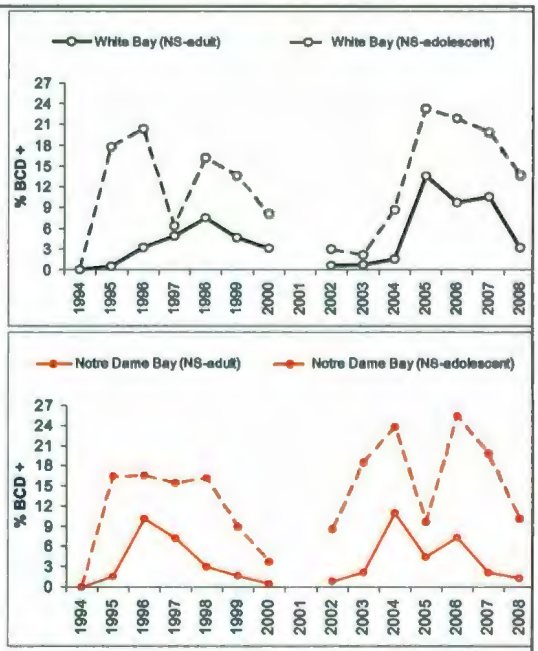

Fig. 13. Trends in prevalence of BCD by bay for new-shelled adult males versus new-shelled adolescent males. White Bay (top) versus Notre Dame Bay (below).

4.6. Depth

Depth strata (Fig. 9) are defined as follows: In White Bay, stratum 615 is shallow (200-300 m), stratum 614 is deep (301-400 m), and stratum 613 is very deep (401-500 m). In Notre Dame Bay, stratum 611 is shallow (200-300 m), and stratum 610 is deep (301-400 m).

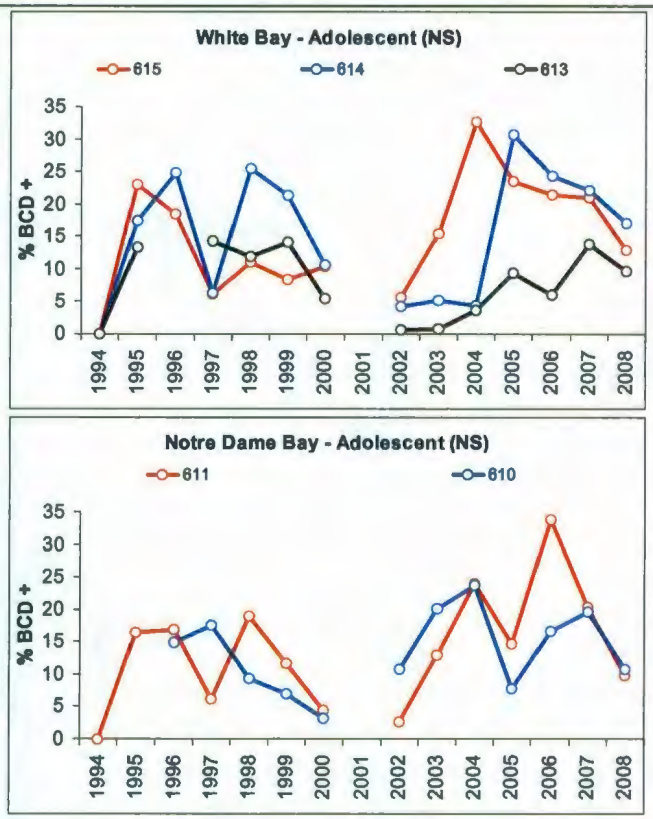

Fig. 14. Trends in prevalence of BCD by bay for new-shelled adolescent males, by survey strata, for White Bay (top) and Notre Dame Bay (below).

In White Bay, there has been spatial-temporal variability across depths and years, with a pattern of peaks in prevalence occurring successively deeper at 1-2 year lags (Fig. 14). For example, the 2004 peak of infection in shallow stratum 615 was followed one year later, in 2005, by a peak in deep stratum 614. This was subsequently followed two years later, in 2007, by a peak in the very deep waters of stratum 613. A similar lag effect across depths occurred in the initial outbreak period of 1995-2000. It is worth noting that maximum prevalence levels are lower in the deepest stratum (613 – about 15%) than in the shallower strata (615, 614 – about 32-33%). This could possibly result from a time-related mortality effect within the population, or it may represent differences in population dynamics in each stratum, such as increasing size at greater depths. The lag effect of prevalence across depths may be a function of circulation features in the bay, or it could reflect migration of crabs.

In Notre Dame Bay, there is no clear discernable pattern in prevalence by depth and year as was evident in White Bay (Fig. 14). Trends in prevalence across both depth strata are generally synchronous, but in some years they oppose one another (ie. 1997, 2007). The reasons for these annual differences are unclear.

4.7. Size

In both bays, a primary mode of 65 mm CW exists in the sample population of adolescents (Fig. 15). The sample distributions of both bays exhibit a positive skew (an elongated right tail), which could be a function of poor representation of smallest crabs. The abundance of crabs, as measured by #/trap, is greater for most sizes of crab in White Bay than in Notre Dame Bay, particularly for the 50-80 mm CW range.

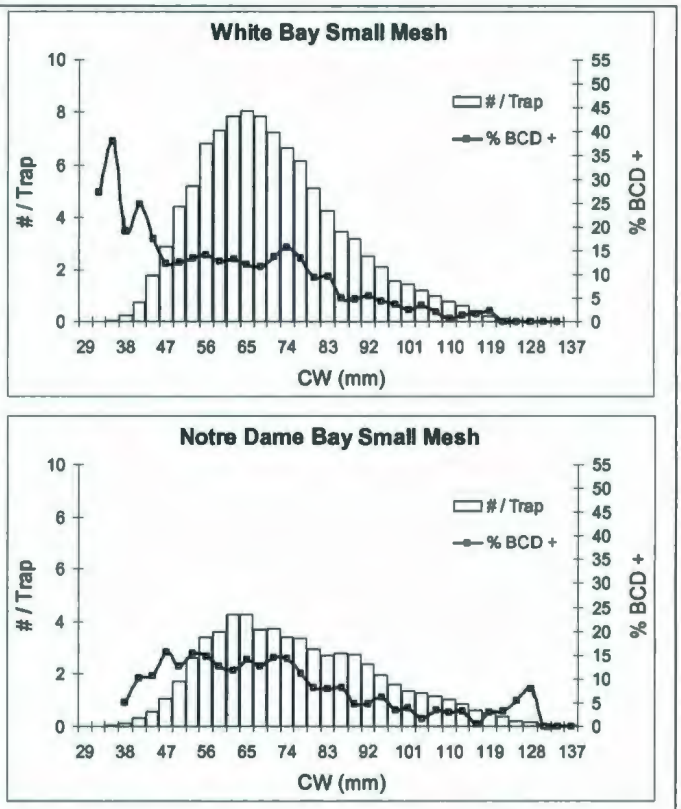

Fig. 15. Survey catch rates versus trends in prevalence of BCD in new-shelled adolescent males, by 3mm carapace width groupings, for White Bay (top) and Notre Dame Bay (below), from 1994-2008.

BCD prevalence exhibits a similar pattern in both bays for crabs =47 mm CW. In both cases, prevalence remains at about 10-15% in 47-74 mm CW crabs. At sizes >74 mm CW, prevalence decreases in successively larger sizes of crabs. Trends in prevalence levels across bays oppose one another for crabs <47 mm CW. In White Bay, prevalence increases as crabs <47 mm CW get smaller, whereas in Notre Dame Bay, prevalence decreases as crabs <47 mm CW get smaller. However, these groups of small crabs are poorly sampled in both bays, thus definitive statements of BCD trends in these smallest crabs are not possible.

Logistic models fit to the data of %BCD by CW show a consistent trend in both bays. Specifically, BCD prevalence decreases with size. These models indicate prevalence is greatest in small crabs, with infection rates of about 25% in 30 mm CW crabs. BCD prevalence is lowest, at about 5% in crabs greater than 130 mm CW. Logistic regression (Table 1, 3) is a probability-based analysis. In this case, it is the probability of crabs of any given size being infected with BCD. The odds ratio (Table 2,

4) is a function of the probability of an event occurring divided by the probability it does not occur (p /1-p). An odds ratio significantly >1.0 indicates the odds of a crab being infected are positively related to the independent variable (CW), while an odds ratio significantly <1.0 indicates the odds of a crab being infected are negatively related to the independent variable. In both White Bay (Table 1) and Notre Dame Bay (Table 3), there is a significant difference by size (CW) in the percentage of crabs infected with BCD, with p<0.0001 in both cases. The odds ratios in both White Bay (OR = 0.977, Table 2) and Notre Dame Bay (OR = 0.975, Table 4) indicate that BCD is negatively related to crab size. Statistically, the probability of a crab being infected with BCD decreases as size increases.

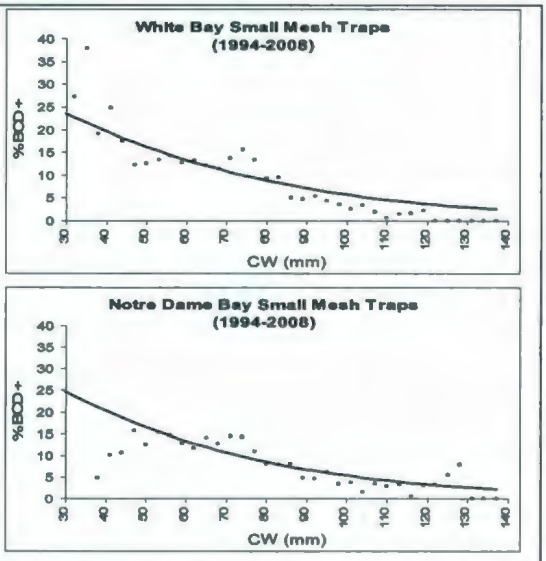

Fig. 16. Logistic regression models of prevalence of BCD in new-shelled adolescent males, by size, for White Bay (top) and Notre Dame Bay (below).

Table 1. Analysis of Maximum Likelihood Estimates for logistic regression testing the effect of carapace width on probability of infection with BCD– White Bay (1994-2008).

Parameter	DF	Estimate	Std. Err.	Wald Chi-Square	Pr > Chi-Square
Intercept	1	-0.4916	0.0625	61.9013	< 0.0001
CW	1	-0.0230	0.00092	622.8039	< 0.0001

Table 2. Odds ratio for logistic regression testing the effect of carapace width on probability of infection with BCD– White Bay (1994-2008).

Effect	Point Estimate	95% Wald Confidence Limits Lower	Upper
CW	0.977	0.976	0.979

Table 3. Analysis of Maximum Likelihood Estimates for logistic regression testing the effect of carapace width on probability of infection with BCD– Notre Dame Bay (1994-2008).

Parameter	DF	Estimate	Std. Err.	Wald Chi-Square	Pr > Chi-Square
Intercept	1	-0.3705	0.1012	13.3963	0.0003
CW	1	-0.0250	0.00141	314.2946	< 0.0001

Table 4. Odds ratio for logistic regression testing the effect of carapace width on probability of infection with BCD– Notre Dame Bay (1994-2008).

Effect	Point Estimate	95% Wald Confidence Limits Lower	Upper
CW	0.975	0.973	0.976

4.8. Salinity and Temperature

There is no clear relationship between BCD prevalence and salinity in any of the survey strata (Fig. 17). Salinity tends to differ with depth, but it does not appear to directly influence trends in BCD prevalence.

In the shallowest strata of both bays (615, 611), salinity tends to be lower than in deeper areas (614, 613, 610). This indicates water nearer to the surface is fresher than water in deeper regions. This could be attributable to melting sea ice, southerly flowing arctic water, or rivers emptying into the ocean. Such phenomena may account for the higher levels of variability in year-to-year salinity levels in the shallower strata than in the deeper strata. Nonetheless, overall, salinity tends to be relatively stable in the region, remaining between 33-35 ppt in all years and at all depths. Salinity in these bays appears to exhibit little

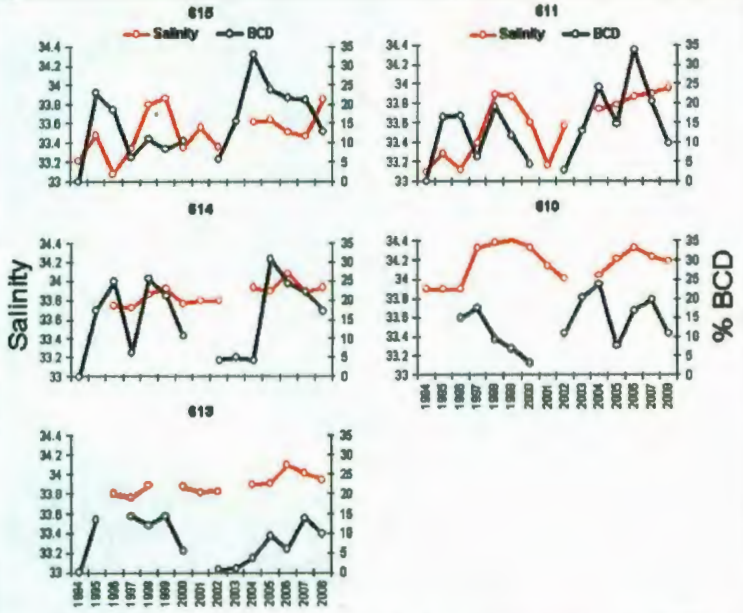

Fig. 17. Comparison of trends in prevalence of BCD in new-shelled adolescent males versus salinity, by survey stratum from 1994-2008. White Bay (left) and Notre Dame Bay (right).

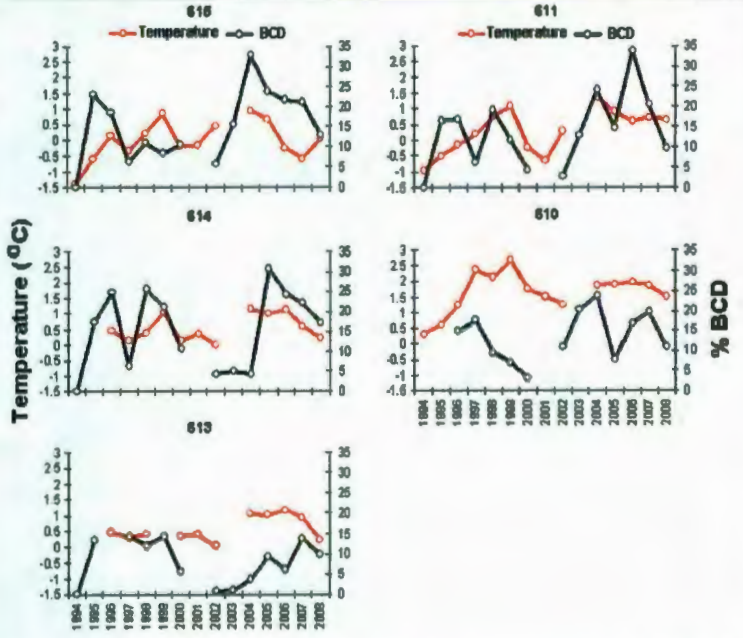

Fig. 18. Comparison of trends in prevalence of BCD in new-shelled adolescent males versus temperature. by survey stratum from 1994-2008. White Bay (left) and Notre Dame Bay (right).

to no effect over BCD prevalence.

As a generalization, these bays are cold areas, with fall bottom temperature ranging between -1.5 to 3°C (Fig. 18). There are annual fluctuations in temperature and differences across depth strata, but they do not appear to directly influence trends in BCD prevalence. For example, in the deep strata (610) of Notre Dame Bay the temperature exceeds 1.5°C in most years, whereas temperature in the shallower strata (611) never achieves this level. Similarly, the deepest strata (613) in White Bay tends to be warmer (0-1°C) in most years than shallower areas such as strata 615, where the water is commonly below 0°C. However, despite these differences there are no clear direct relationships between BCD prevalence and temperature.

4.9. Distribution / Migration

A deepward migration occurs as crabs age and grow. These ontogenetic movements can be detected by following the progression of modes in size frequencies (Fig. 19). For example, a primary mode at 50mm CW in 2006 in stratum 615 of White Bay (200-300 m) was followed by a primary mode at 59 mm CW in deep stratum 614 (301-400 m) in 2007. This mode subsequently progressed further, to 80 mm CW, in the very deep stratum 613 (401-500 m) in 2008. When all years of data are pooled, these deepward migrations result in a distribution pattern with segregation by size and depth in both bays (Fig. 20), as successively larger crabs are found in successively deeper strata. The association of this size-depth pattern with BCD prevalence and temperature is detailed in the next section.

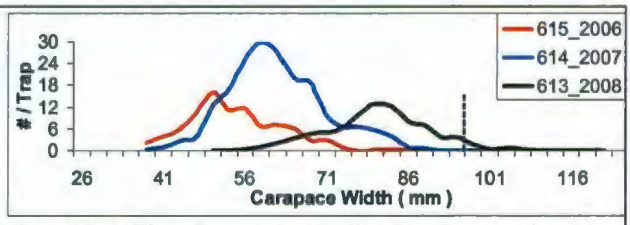

Fig. 19. Size frequency distributions of new-shelled males in White Bay. Data selected to track a pseudo-cohort across depths and years.

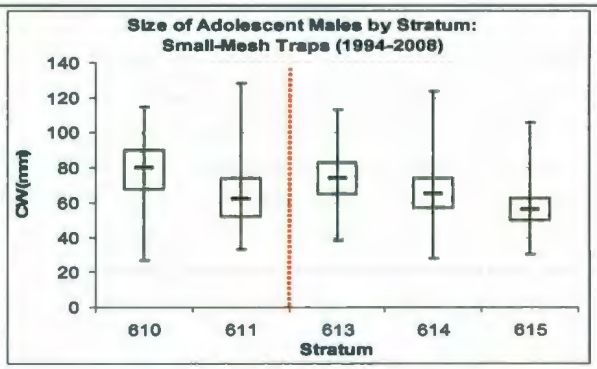

Fig. 20. Box and Whisker plots for sizes of new-shelled males in each survey stratum (1994-2008). Red line separates bays. Horizontal lines inside boxes = medians; boxes = Q1, Q3; Whiskers = min, max.

4.10. Size / Depth / Temperature

The size-depth stratification of male crabs closely reflects a size-temperature stratification in both bays, as successively larger crabs are distributed at successively higher temperatures, corresponding to successively greater depths (Fig. 21). In this respect, temperature is correlated with depth, and there is a size-depth-temperature interaction that affects the distribution of crabs.

The pattern of increasing size with temperature produces a negative relationship between BCD prevalence and temperature because prevalence is negatively related to size (Fig. 22). A lack of consideration of size is likely the reason no direct relationships of prevalence with temperature were found (Fig. 18). Temperature does not work directly to control prevalence levels of BCD, but is indirectly associated with BCD prevalence via its relationships with depth and size. As variability in the size structure of crabs by depth and temperature influences trends in BCD prevalence, it is likely that differences in the spatial and temporal density of different sizes of crabs is a determining factor regulating for prevalence of BCD. This relationship is investigated in the next section.

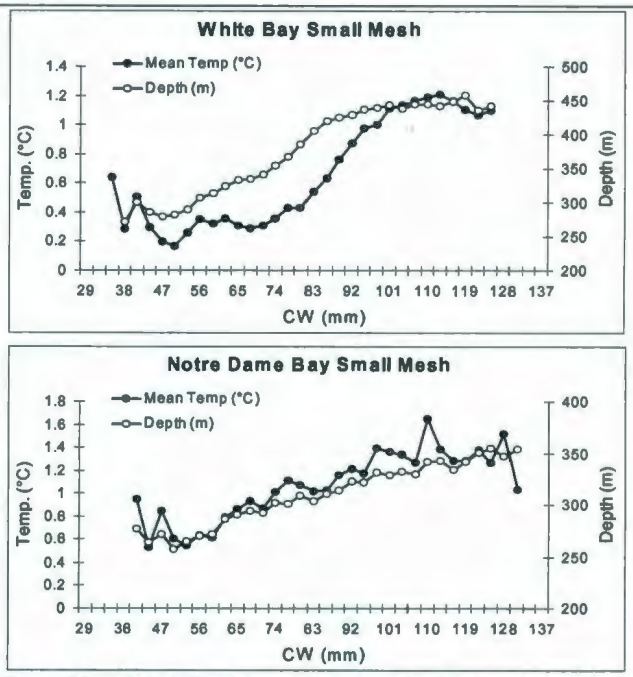

Fig. 21. Distribution of new-shelled adolescent males by size relative to temperature and depth in White Bay (top) and Notre Dame Bay (bottom). *Note: Data only for 2004-2008 as no temperature information collected before 2004.*

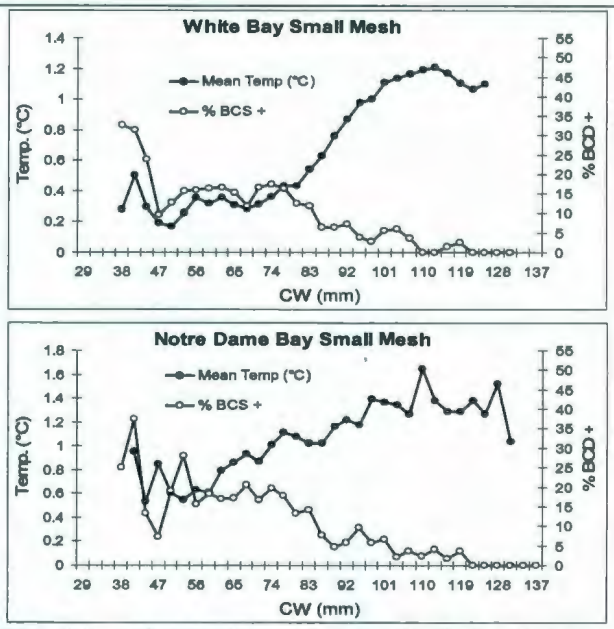

Fig. 22. Distribution of new-shelled adolescent males by size and temperature versus prevalence of BCD by size and temperature in White Bay (top) and Notre Dame Bay (bottom). *Note: Data only for 2004-2008 as no temperature information collected before 2004.*

4.11 Host Density

There is a positive relationship between % BCD and the density of small to intermediate-sized new-shelled crabs (adolescents and adults) in the population (Fig. 23). A power-type function ($y=2.15X^{0.401}$) provided the best fit ($r^2=0.53$) for the relationship of %BCD (by stratum and year) regressed on CPUE. Data from the 2004 survey were omitted from analysis due to low trap catchability and resultant anomalously low CPUE values in all survey strata in that year (Dawe et al. 2009a).

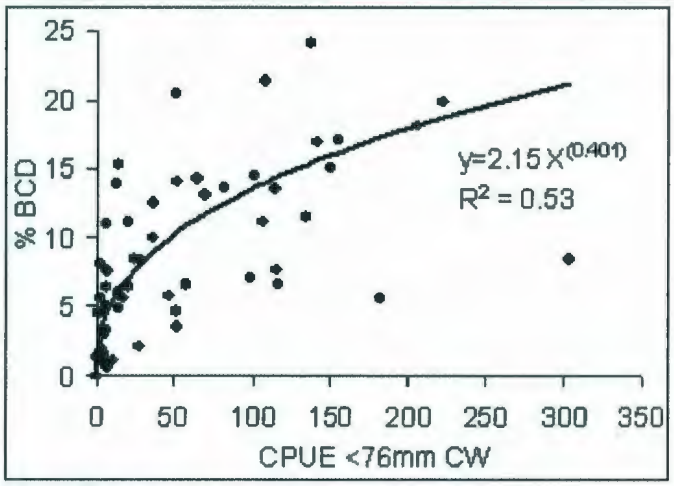

Fig. 23. Regression analysis describing the relationship between % BCD and CPUE of <76mm CW new-shelled males, by stratum and year, in White Bay and Notre Dame Bay (1994-2008). *Note: 2004 data omitted due to low trap catchability and anomalous CPUEs.*

	Source	DF	Type II SS	F	P
all sizes	CPUE	1	2.35	6.58	0.0143
	Strat	4	1.23	0.86	0.4936
	Year	11	13.6	3.47	0.002
< 76mm CW	CPUE	1	6.55	26.34	<.0001
	Strat	4	2.16	2.17	0.0909
	Year	11	10.73	3.92	0.0007

Table 5. Linear regression models examining the effects of CPUE, year, and stratum on prevalence of BCD in new-shelled males in White Bay and Notre Dame Bay. Analysis conducted using CPUE of all sizes of new-shelled males (above) and small to intermediate-sized new-shelled males (<76mm CW) (below). *Note: 2004 data omitted due to low trap catchability and anomalous CPUEs.*

Linear regression (ANCOVA) was used to analyze factors affecting % BCD in the population (Table 5), using pooled data from both bays. Data on %BCD and CPUE were log transformed prior to analysis to achieve linearity. The models regressed % BCD on CPUE, and included year and strata as additional explanatory variables. The models show that the relationship of %BCD with CPUE was significant ($p<0.05$, Table 5). The main effect of year also contributed significantly to explaining the variability in %BCD whereas stratum did not ($p>0.05$, Table 5). The covariate CPUE was the most significant variable in both models, and was strongest in the model for <76 mm CW crabs ($p <0.0001$), indicating

that the density of small to intermediate-sized new-shelled crabs accounts for most of the variability in BCD prevalence.

4.12. Impacts of BCD on the Fishery

By tracking prevalence of BCD in small to intermediate-sized adolescent crabs across years, one can predict with some certainty the success of the future fishery. An examination of proportional year-to-year changes in % BCD in <76 mm CW crabs in relation to changes in future fishery catch rates reveals an association in both bays (Fig. 24). It should be noted CPUEs represent only deep strata (610, 614, 613), and catch rates of =95mm CW intermediate & old-shelled crabs, in order to represent where the fishery occurs and the portion of the population constituting commercial crabs. The agreement in trends in both bays is striking, especially considering the crude nature of both indices, and the high levels of variability that can independently occur in both. In this respect, BCD prevalence in small to intermediate-sized adolescents acts as a signal of recruitment. A high level of BCD in the population is indicative of a high level of mid to long-term recruitment, and vice versa.

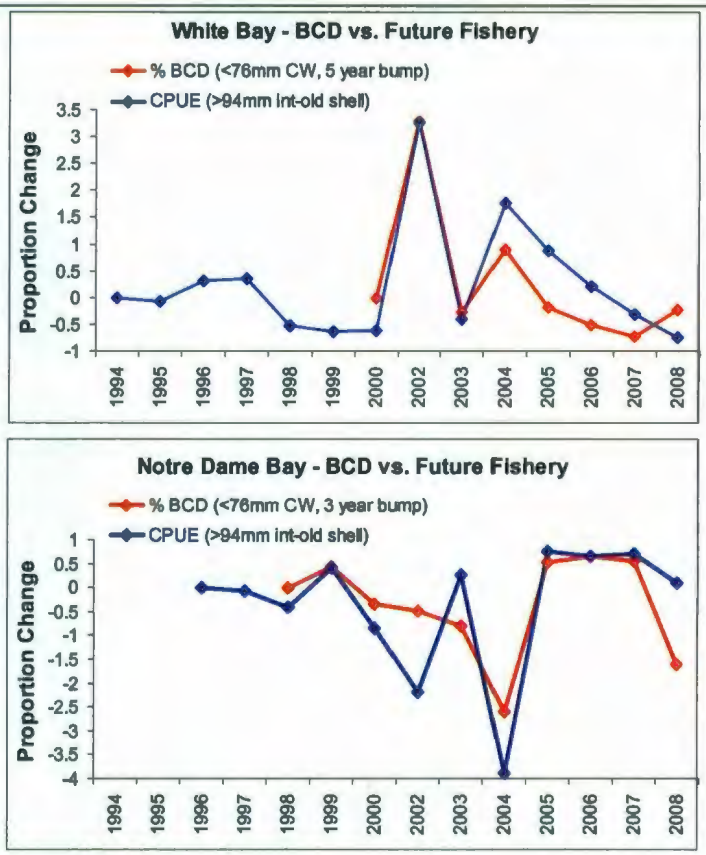

Fig. 24. Trends in proportional changes of year-to-year catch rates of commercial (>94mm CW intermediate to old-shelled) crabs in the survey versus proportional changes in %BCD in new-shelled adolescent males 3 years later in White Bay (top) and 5 years later in Notre Dame Bay (below).

The differences in timing for best-fit of trends across the two bays is interesting, with a forward shift of %BCD by five years in White Bay and three years in Notre Dame Bay (Fig. 24). This likely represents differences in molting schedules and growth rates,

and time necessary to reach legal size for crabs in both bays. Variability in molting schedules and growth rates is a common feature when comparing snow crab populations in different regions. Environmental and oceanographic features are thought to influence the matter, with molting more frequent in warmer waters. This is consistent with warmer temperatures in stratum 610 of Notre Dame Bay than in stratum 613 and 614 of White Bay (Fig. 18).

4.13. Conclusions of Research

Results of research examining potential abiotic and biotic factors affecting prevalence levels of BCD in snow crab in White and Notre Dame Bays indicates that density of small to intermediate-sized crabs is the factor directly controlling for prevalence levels of BCD in the population. All other factors either do not influence, or exhibit indirect influences over prevalence, as they can influence the annual density and distribution of small to intermediate-sized crabs.

5.0. Recommendations and Management Considerations

5.1 Recommendation #1:

Avoid BCD in the fishery. Fish when prevalence and intensity are lowest.

In Newfoundland and Labrador, the optimal time to harvest snow crab would be in the spring, immediately following the retreat of winter sea ice. This would allow for crabs to be harvested when they are not intensely parasitized, and thus most marketable. A spring fishery would also serve to help minimize the handling &/or discarding of infected animals (which may spread the disease), and lower fishery exploitation rates, as additional quota would not have to be allotted to account for infected crabs captured in the fishery.

5.2 Recommendation #2:

Consider BCD in planning mid to long-term harvesting strategies.

BCD acts as a signal of mid to long-term recruitment. When prevalence is high, recruitment is strong, and when prevalence is low, recruitment is weak. In this regard, tracking BCD prevalence levels can help predict the success of future fisheries. A strategy of gradually reducing quotas following years of low BCD prevalence may serve

to increase or maintain the residual biomass to a level sufficient enough to minimize 'shock' effects in the fishery during periods of low recruitment. This would also serve to help stabilize the future stream of economic returns from the fishery.

5.3 Recommendation #3:

Invest in research on BCD.

There is little doubt prevalence levels of BCD are being underestimated. Maximum yearly prevalence in this report was shown to be about 35%, but true prevalence levels could be as much as 2x higher than that. As BCD is fatal, this disease should be regarded as a significant regulating factor for snow crab populations. As such, increased knowledge on true prevalence levels and basic biology and pathology of infection are critical toward developing more effective biological and management strategies to deal with it.

5.4 Recommendation #4:

Educate the industry about BCD.

There is enough information on BCD to know it has a negative biological impact, and the potential to exert great negative economic impacts over the fishery. Snow crab harvesters should be made more fully aware of what BCD is, how to detect it, and encouraged to report it if found. It should be made clear to harvesters that an earlier (spring) season is beneficial for avoiding high incidence of the disease in the fishery, and that reporting catches of diseased crabs may help scientists and managers more effectively plan harvesting strategies. For the same reasons, the processing sector should be more highly educated on BCD.

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